PCT

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(54) Title: MULTI-PATH INTERFERENCE FILTER
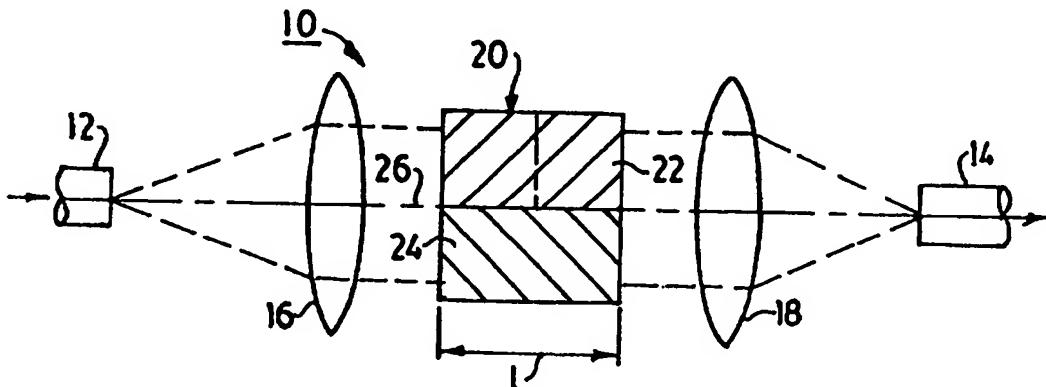
(57) Abstract

An interference filter (10, 30, 50, 70, 90, 110, 130, 150, or 190) filters selected wavelengths by dividing an input beam into two or more intermediate beams having different optical path lengths and by recombining the intermediate beams into an output beam that is modified by interference between the intermediate beams. An optical path length difference generator (20, 40, 60, 80, 100, 120, 140, 160, or 200) varies the optical path lengths of the intermediate beams by changing the physical lengths of their paths or the refractive indices of the mediums in which they are conveyed. The optical path length generator (20) of one exemplary embodiment (10) includes a spacer plate (20) that is divided into solid optical elements (22 and 24) having different refractive indices for varying the optical path lengths of the intermediate beams. Another optical path length difference generator (140) is formed by a stack of partially reflective surfaces (144) that are spaced apart in the direction of beam propagation by at least one nominal wavelength for varying the physical path lengths between the intermediate beams.

MULTI-PATH INTERFERENCE FILTER

Technical Field

The invention relates to optical devices for filtering selected wavelengths of light using the mechanism of interference.

5 ## Background

Interference filters use combinations of constructive and destructive interference to shape filter responses. Wavelengths subject to constructive interference pass through the filters, and wavelengths subject to destructive interference are blocked. The
10 interference is created by overlapping different phase-shifted portions of the same beam. Examples include Fabry-Perot etalons, dielectric filters, and fiber Bragg gratings.

Fabry-Perot etalons use pairs of opposing partially reflective surfaces to produce multiple interference between reflected beam
15 portions. However, the filter response is limited. Sinusoidal response curves are typical. Manufacturing is complicated by a requirement for precise alignment of the reflective surfaces.

Both dielectric filters and fiber Bragg gratings have alternating layers of high and low refractive index to produce a
20 series of partial reflections that are offset by the spacing between the layers. Typically, the layers are spaced apart by one-quarter of the nominal wavelength of the filtered beam, which is difficult to hold for assembly of dielectric filters. Conventional manufacturing of the dielectric filters is limited to bulk optics, which are
25 generally more costly than comparable integrated optics.

The index variation of fiber Bragg gratings is very low (e.g., .0001) so a very large number of layers are required to attenuate unwanted wavelengths. The alternating layers are made by exposing a photosensitive material to a standing wave. This limits the choice
30 of materials to those which are photosensitive.

2

U.S. Patent 4,715,027 to Mahapatra et al. discloses a multi/demultiplexer that can also be arranged as a filter. An echelon grating has reflective surfaces arranged in a staircase to reflect light back to a source at equally spaced frequencies.

5   Although the filter can be manufactured as an integrated optic, its response is also limited. The filters must be cascaded in succession similar to a vernier to further refine the response.

Summary of Invention

My invention also filters selected wavelengths of light by
10   dividing a input beam of light into two or more intermediate beams having different optical path lengths and by recombining the intermediate beams into an output beam that is modified from the input beam by interference between the intermediate beams. The optical path lengths of the intermediate beams can be varied by
15   altering either the physical lengths of their respective paths or the refractive indices of the mediums in which they are conveyed.

My multi-path filter includes input and output optical pathways and an optical path length difference generator. One or more focusing optics can be used to couple the optical path length
20   difference generator to the input and output pathways. For example, the input and output optical pathways can be aligned with an optical axis together with a pair of focusing optics and a spacer plate that functions as the optical path length difference generator. The first focusing optic collimates an expanding input beam emitted from the
25   input pathway. The spacer plate has two or more intermediate pathways that divide the collimated beam into a corresponding number of intermediate beams having different optical path lengths. The second focusing optic converges and recombines the intermediate beams at a focus on the output optical pathway.

30   Another configuration of my multi-path filter includes adjacent input and output optical pathways that are offset from the optical axis. A single focusing optic cooperates with a spacer plate and a reflective optic for both collimating an input beam from the input pathway and focusing returning intermediate beams on the

output pathway. With the addition of the reflective optic, the intermediate beams traverse the spacer plate two times, thereby doubling the differences between their optical path lengths. Alternatively, the reflective optic can be curved to also perform the

5   functions of the focusing optic. A diverging beam from the input pathway is reflected on a return course through the intermediate pathways as a converging beam to the output pathway.

The intermediate pathways of the spacer plate can be varied in number, material, transverse area, and longitudinal length for

10   achieving a desired spectral response. Optical path length differences between intermediate beams are created by varying the refractive indices of the materials forming the intermediate pathways, by varying their length, or both. The transverse areas of the intermediate pathways control the relative energies of the

15   intermediate beams, and the number of different intermediate pathways controls the number of intermediate beams that can contribute to the desired spectral response. In general, the number of intermediate pathways is analogous to the number of slits in a conventional interference model.

20   In place of the spacer plate, a reflective stack can be used to generate optical path length differences between the intermediate beams. Each layer of the reflective stack has a reflective coating that reflects a portion of the total light that is incident to the stack. The partial reflections provide a plurality of intermediate

25   pathways that overlap spatially but separate the intermediate beams through different physical path lengths of at least one wavelength. The number, material, partial reflectivity, and longitudinal length of each layer can be controlled to adjust the spectral response.

My filter can be implemented in bulk optics, integrated optics,

30   or in various hybrid combinations. For example, all of the elements can be constructed in planar technology. However, separately oriented elements are preferably used for more accurately reflecting light parallel to the other elements. My filter can also be incorporated within a single fiber. Two focusing optics and a spacer

4

functioning as an optical path length difference generator are fusion spliced to join two ends of the fiber.

Materials within the spacer of the fiber or other implementation can be combined to exhibit different index
5   characteristics with externally controlled conditions such as temperature, pressure, or electrical or magnetic fields. The controlled variation in the index difference between different intermediate pathways can be used for tuning the filter response to selected wavelengths.

10   **Drawings**

Fig. 1 is an optical diagram of my multi-path interference filter using a two-part spacer block for generating optical path length differences between axially aligned input and output fibers.

Fig. 2 is a graph of an exemplary spectral response of my filter
15   as a measure of transmitted intensity over a domain of wavelengths.

Fig. 3 is an optical diagram of a similar interference filter with an alternative spacer block.

Fig. 4 is an optical diagram of a similar multi-path interference filter with an alternative spacer block having two
20   concentric elements.

Fig. 5 is an optical diagram of my multi-path interference filter with adjacent input and output fibers optically connected by an alternative spacer block and a reflective optic.

Fig. 6 is an optical diagram of a similar interference filter in
25   which an alternative spacer block includes additional elements for providing a more complex spectral response.

Fig. 7 is a graph similar to the graph of Fig. 2 but showing a more complex spectral response provided by the additional spacer block elements.

Fig. 8 is an optical diagram of a similar interference filter with an alternative spacer block for providing a complex spectral response.

Fig. 9 is an optical diagram of my multi-path interference
5   filter in which a reflective stack functions as an optical path length difference generator.

Fig. 10 is a cross-sectional view of an optical fiber incorporating my multi-path interference filter formed by two GRIN lenses and a spacer that generates optical path length differences.

10   Fig. 11 is a sectional view along line 11-11 through the spacer showing two different optical segments for providing the different length paths.

Fig. 12 is a similar sectional view of an alternative spacer enclosed by two electrodes for tuning the filter's spectral response.

15   Fig. 13 is a cross-sectional view of a single mode fiber fused to a multi-mode fiber with a gaussian index profile.

Fig. 14 is a cross-sectional view of the same two fibers with the multi-mode fiber cleaved to a length appropriate for use as a GRIN fiber rod lens.

20   Fig. 15 is an optical diagram of an interference filter similar to the filter of Figs. 4-6 with a reflective surface shaped to take on the functions of a focusing optic.

Detailed Description

One embodiment of my invention as a multi-path filter 10
25   implemented in bulk optics is illustrated by Fig. 1. The illustrated filter 10 has single-mode input and output fibers 12 and 14 (input and output pathways) optically coupled by two lenses 16 and 18 (focusing optics) and a spacer plate 20 that functions as an optical path length difference generator. The first lens 16 changes an
30   expanding input beam from the input fiber 12 into a collimated beam that strikes the spacer plate 20 at normal incidence.

6

The spacer plate 20 is divided into two different optical elements 22 and 24 (intermediate pathways) that extend parallel to different transverse sections of the collimated beam. The element 22 is formed by a material having a first refractive index "n_1", and
5   the element 24 is formed by a material having a second refractive index "n_2". The two elements 22 and 24 of the spacer plate 20 divide the collimated beam into parallel intermediate beams having different optical path lengths as determined by the following equation:

10   (1) $\Delta OPL = L(n_1 - n_2)$

where "ΔOPL" is the optical path length difference of the two intermediate beams and "L" is the longitudinal length of the spacer plate in the direction of propagation.

The second lens 18 converges and recombines the two
15   intermediate beams to a focus at the inner end of the output fiber 14, which is located along a common optical axis 26 with the input fiber 12. When recombined, constructive interference occurs periodically at wavelengths "λ" that are integer multiples "M" of the path length difference "ΔOPL". Expressed mathematically:

20   (2) $\Delta OPL = M\lambda$

A typical spectral response curve for the filter 10 is shown in Fig. 2. The original spectral power distribution of the beam entering the filter 10 is assumed to be even throughout the domain of measured wavelengths. The response curve 28, which reflects the
25   spectral power distribution of the beam upon exiting the filter 10, has a cyclical form with peak intensities located at wavelengths subject to maximum constructive interference between the beams, i.e., the wavelengths that are integer multiples of the path length difference. All other wavelengths are subject to varying degrees of
30   destructive interference. A preferred range for the multiple "M" is between 20 and 150.

Another multi-pass filter 30, which is shown in Fig. 3, includes similar input and output fibers 32 and 34 and lenses 36 and

7

38 but a different spacer plate 40. The spacer plate 40 is made from a base element 42 and an extension element 44 that distinguishes the spacer plate 40 in the transverse direction. Assuming that the base element 42 is homogeneous, the only dimension of interest to
5   the optical path length difference is the dimension "L" of the extension element 44. Equation (1) continues to apply. However, the refractive index "n_1" is taken as unity and the refractive index "n_2" is determined from the material of the extension element 44.

Fig. 4 illustrates another filter 50 with similar input and
10   output fibers 52 and 54 and lenses 56 and 58. The spectral response function is also similar. However, the optical path length difference is generated by a spacer plate 60 made from two concentric elements 62 and 64 that occupy different transverse areas of aperture 66. The element 62, which has a cylindrical shape, is
15   surrounded by annular-shaped element 64. Each of the elements 62 and 64 is made from a different material - one of which could even be air, but both elements share a common length "L".

Contrast between the respective intensities of the transmitted and non-transmitted wavelengths can be controlled by adjusting the
20   transverse areas of the two elements 62 and 64. The respective areas are adjusted by changing the relative sizes of effective radii "r_1" and "r_2" of the two elements 62 and 64. For example, contrast can be maximized by relating the respective areas to the intensity profile of the incident collimated beam to balance spectral energies
25   transmitted by the two elements 62 and 64. The concentric shapes of the two elements 62 and 64 simplify the division of power within beams having radially symmetric power distributions.

A multi-pass filter 70 illustrated by Fig. 5 is different in several respects. Input and output fibers 72 and 74 are located next
30   to each other on the same side of a single lens 76 but on opposite sides of (i.e., straddle) an optical axis 68. The input fiber 72 emits a diverging beam that is collimated by the single lens 76. A reflective optic 78 retroreflects the collimated beam after passing through a spacer plate 80. Upon its return, the collimated beam is reconverged
35   by the single lens 76 to a focus at the output fiber 74. To maximize

8

coupling efficiency, the input and output fibers 72 and 74 can be inclined toward the optical axis 68 in longitudinal alignment with an intersection between the optical axis 68 and the reflective optic 78.

5   The reflective optic 78 can be formed as a separate mirror or as a reflective coating on a remote surface of the spacer plate 80. Elements 82 and 84 of the spacer plate 80 are concentric but differ in both dimensions of length "L_1" and "L_2" and in material composition (i.e., n_1 and n_2). The resulting optical path difference "ΔOPL" accounting for the reflection can be expressed as follows:

10   (3) $\Delta OPL = 2 L_1 (n_1 - 1) - 2 L_2 (n_2 - 1)$

Despite all of these changes, a spectral response curve similar to Fig. 2 is still possible with a contrast governed by radii "r_1" and "r_2". Other shapes and sizes of the spacer elements 82 and 84 could also be used to generate the required optical path length differences.

15   The single lens 76 could be obviated by shaping the reflective optic as a sphere for reflecting light emanating from the input fiber 72 on a return course to the output fiber 74. The spacer elements 82 and 84 would be reshaped along radial lines to divide portions of the diverging and converging beams.

20   Fig. 6 depicts a multi-path filter 90 that includes a similar arrangement of input and output fibers 92 and 94, together with a single lens 96 and a reflective element 98 associated with a spacer plate 100 for retroreflecting light emitted by the input fiber 92 on a return course to the output fiber 94. The spacer plate 100 is

25 distinguished by multiple annular elements 102, 104, 106, and 108 that vary in length from "L_1" to "L_n" and that vary in radius from "r_1" to "r_n". Respective indices "n_1" to "n_n" of the annular elements 102, 104, 106, and 108 can be the same or varied. If the same, the optical path lengths of the corresponding intermediate pathways are

30 varied by the same combinations of materials (e.g., glass and air) but in different proportions for exhibiting different effective refractive indices.

9

The result is a more complex pattern of interference generated by the combination of additional intermediate beams having respective optical path lengths relatively varied by the annular elements 102, 104, 106, and 108 of the spacer plate 100. An

5   exemplary spectral response curve 88 of transmitted intensities over a domain of wavelengths is shown in Fig. 7. Here, the peak intensities are narrower and more widely spaced than in the response curve of Fig. 2. Further control over the shape of the response curve 88 can be achieved by relatively adjusting the

10   lengths "L_1" to "L_n", the indices "n_1" to "n_n", or the radii "r_1" to "r_n" of the annular elements 102, 104, 106, and 108. Variations in the lengths "L_1" to "L_n" or the indices "n_1" to "n_n" affect the optical path lengths of the intermediate beams and variations in the radii "r_1" to "r_n" affect their relative power.

15   The intermediate pathways through the respective optical path length difference generators of all five of the preceding filters illustrated by FIGS. 1-6 have equal physical path lengths but different effective indices of refraction. The spacer plates 20 and 60 form equal length intermediate pathways that are distinguished by different materials. The spacer plates 30, 70, and 90 form equal

20   length intermediate pathways that are distinguished by different combinations of materials, including combinations that vary only in proportion. The materials themselves can differ in composition or even physical states, such as glass and air.

25   A multi-path filter 110 depicted in Fig. 8 is similar in most respects to the multi-path filter 90 including input and output fibers 112 and 114, a single lens 116, a reflective element 118, and a spacer plate 120. Also similar to the multi-path filter 90, the spacer plate 120 is composed of multiple annular elements 122,

30   124, 126, and 128 that vary in length from "L_1" to "L_n" and that vary in radius from "r_1" to "r_n". Respective indices "n_1" to "n_n" of the annular elements 122, 124, 126, and 128 can be the same or different.

However, in contrast to all of the preceding embodiments, the

35   relative positions of the annular elements 122, 124, 126, and 128,

together with their common reflective element 118, also change the physical path lengths of the intermediate beams by the differences in their lengths "L_1" to "L_n". For example, the optical path length difference between annular elements 122 and 128 can be expressed

5   as follows:

$$(4) \qquad \Delta OPL = 2 (L_1 \, n_1 - L_n \, n_n)$$

To accommodate the different length annular elements 122, 124, 126, and 128, the reflective element 118 is stepped. This is most easily accomplished by applying a reflective coating to the end

10   faces of the annular elements 122, 124, 126, and 128. If a plane mirror is used instead, the physical path lengths of the intermediate beams are equated similar to the embodiment of Fig. 6.

Similar to the embodiments of FIGS. 5 and 6, the single lens 116 can be obviated by reshaping the reflective element 118.

15   However, instead of shaping the reflective element 118 as a continuous curved surface, the annular steps of the reflective element 118 are preferably individually curved to provide a similar focusing function. The annular elements 122, 124, 126, and 128 would be tapered along radial lines to a primary focus.

20   In any one of the preceding embodiments, the single lenses can be replaced by diffractive optics or even diffraction patterns inscribed on the spacers. If inscribed on the reflective surfaces, the intermediate pathways would be shaped to follow the lines of focus.

Like all of the preceding embodiments, the embodiment of Fig.

25   9 is a multi-path filter 130 having input and output fibers 132 and 134 along with a lens 136 or its equivalent. However, the optical path length difference generator is a reflective stack 140 instead of a spacer plate. The reflective stack 140 is made in layers 142 separated by partially reflective surfaces 144. Each of the layers

30   142 has a constant length "L" and a constant index "n", although both the length "L" and the index "n" could be varied between the layers 142 to provide a more complex spectral response.

11

The reflectivity of the partially reflective surfaces 144 is related to the number of layers 142 required to establish the desired spectral response. For example, if 20 of the layers 142 are required, then each of the reflective surfaces 144 is made to reflect about

5   five percent of the overall spectral energy. The number of layers 142 is analogous to the number of intermediate pathways through the spacer plates of the preceding embodiments, and the reflectivity of each of the layers 142 is related to the transverse areas of the intermediate pathways. However, the intermediate beams can be

10 separated by less distinct areas of each partially reflective surface 144.

In other words, the intermediate beams can occupy virtually the same space, e.g., the entire aperture "A", upon entry and exit of the reflective stack 140. However, their respective optical path

15 lengths are distinguished by different physical lengths of travel along an optical axis 146 corresponding to a multiple of the length "L". Thus, the equation for optical path length difference between two intermediate beams from adjacent layers 142 is given by:

$$(5) \qquad \Delta OPL = 2 L n$$

20   The intermediate beams should be separated by an optical path difference "ΔOPL" of at least one wavelength of the propagating light beam. Spacings of at least 10 microns are preferred with average thicknesses expected in the range of 20 to 30 microns. The reflective surfaces 144 can be formed by partially reflective

25 coatings, fully reflective coatings (e.g., metallic spots) applied to limited transverse areas, or adjacent material layers having large differences in refractive index. Refractive index differences of at least 1 percent should be used to limit the number of layers required to reflect substantially all of the propagating beam, but differences

30 of 10 percent or more are preferred for constructing practical spectral responses. No more than 100 layers are preferably used.

Additional details regarding the construction and manufacture of similar reflective stacks is contained in my copending U.S. Provisional Patent Application No. 60/012,170 filed 23 February

1996 and entitled "Multiple Reflection Multiplexer and Demulti-
plexer". This application is hereby incorporated by reference.

Although all of the above embodiments are depicted in bulk
optics, the same embodiments could also be implemented with
5   integrated or hybrid optics. For example, the input and output fibers
could be formed as waveguides on a substrate that also contains one
or more focusing and reflecting optics, as well as the optical path
length difference generator. As a hybrid design, the input and output
fibers and the one or more focusing optics could be formed on a first
10   substrate and the optical path length difference generator could be
formed on a second substrate. Alternatively, the first substrate
could also incorporate the optical path length difference generator,
and the reflective element could be formed separately as a bulk
optic mounted against a wall of the first substrate or as a reflective
15   coating on the same wall. The focusing optic could also be a curved
reflective optic that is formed separately or as a part of the same
integrated device.

Angular tolerances must be tight to assure proper focusing
between the input and output pathways. However, more leeway exits
20   with lateral and longitudinal dimensions. For example, the lateral
position of the spacer plate affects the distribution of light between
the intermediate beams, but small variations have only a limited
effect on the spectral response. Similarly, the length dimension "L"
can measure as much as 0.25 mm, so small variations in the range of
25   microns are of limited significance.

My invention can also be formed as a part of a single mode
optical fiber as shown in Figs. 10 and 11. A multi-path interference
filter 150 is formed between adjacent ends 152 and 154 of the
single mode fiber. GRIN (gradient index) fiber rod lenses 156 and
30   158 and a central spacer 160 that functions as an optical path length
difference generator are fusion spliced between the adjacent ends
152 and 154.

In one direction of light travel, the GRIN lens 156 collimates
light emitted from fiber end 152. The spacer segment 160 is divided
35   into two axial segments 162 and 164 (intermediate pathways) that

13

extend between the GRIN lenses 156 and 158. Each of the segments is made from a different material and includes a different refractive index "n_1" and "n_2" - at least within the range of wavelengths intended for use. A jacket 166 can be used to encapsulate the two
5   segments 162 and 164, so their respective materials can be in various states including solid and liquid or solid and gas. Photosensitive (e.g., GeO_2 - SiO_2) or electro-optic (e.g., liquid crystal) materials could also be used.

Similar to the earlier embodiments 10, 30, 50, and 70, the two
10   segments 162 and 164 divide the collimated light into two intermediate beams having different optical path lengths. The GRIN lens 158 recombines the two intermediate beams at a focus on the single mode fiber end 154. The resulting interference between the combined beams in the fiber end 154 produces a spectral response
15   similar to that illustrated in Fig. 2. Additional segments occupying differing amounts of aperture area can be used to provide a more complex response.

Tuning can be accomplished by using one or more materials whose index varies with temperature, pressure, or electrical or
20   magnetic fields. For example, Fig. 12 shows a cross section of an alternative spacer 170 having two concentric segments 172 and 174 and a jacket 176 partly surrounded by metal electrodes 178 and 180. The inner segment 172 is made of glass, and the outer segment 174 is made of a polymer that exhibits variations in refractive index
25   with temperature. Varying the temperature of the polymer with the electrodes changes the optical path length difference between the segments 172 and 174 and thereby alters the spectral response of the filter.

Figs. 13 and 14 illustrate how to make a GRIN fiber rod lens
30   182. A length (approximately 10 cm to 20 cm) of graded index fiber 184 is fusion spliced to a single mode fiber 186. The graded index fiber 184 has an index that varies radially according to a gaussian profile. The graded index fiber 184 is mechanically cleaved along line 188 to a length "LG" that is equal to one-quarter of a complete
35   cycle for refocusing a point source along the optical axis. At the

14

specified length, light from the point source (i.e., the end of the single mode fiber) is collimated. Further information about GRIN fiber rod lenses can be found in an article by W. L. Emkey and C. A. Jack entitled "Analysis and Evaluation of Graded-Index Fiber Lenses"

5   from Journal of Lightwave Technology LT-5, 1987, pages 1156-1164. This article is hereby incorporated by reference.

Fig. 15 depicts another embodiment 190 of my multi-path filter, which accomplishes the focusing function in a different way. Similar to the embodiments 70 and 90 of Figs. 5 and 6, a reflective

10   surface 198 couples adjacent input and output fibers 192 and 194, which straddle an optical axis 196. However, the reflective surface 198 is curved (preferably spherical in bulk implementations) to also provide the focusing function. A diverging beam emitted by the input fiber 192 is substantially retroreflected by the reflective surface

15   198 on a converging path to the output fiber 194.

A spacer 200 supporting the reflective surface 198 along the optical axis 196 is composed of symmetric (or concentric) optical elements 202 and 204, which have different refractive indices. The optical elements 202 and 204, which form portions of equal length

20   intermediate pathways connecting the input and output fibers 192 and 194, converge toward a focal point 206 of the reflective surface 198. The different refractive indices of the optical elements 202 and 204 vary the optical path lengths of the intermediate pathways for producing a pattern of interference that varies the spectral

25   power distribution of the recombined beam reaching the output fiber 194.

A similar focusing function could be performed by a plurality of individual reflectives that are offset along an optical axis such as shown in Fig. 8 but oriented to a common focal point. The offset

30   would produce physical path length differences between the intermediate pathways in addition to or as a substitution for differences in refractive index.

My invention in its various embodiments can be used in a variety of filtering applications over a broad range of wavelengths

35   (e.g., 1200 nm-1700 nm) including applications in the fields of

communication and sensing technologies. One such application is in conjunction with an optical amplifier for amplifying specific wavelengths isolated by my filter.

I claim:

1. A multi-path interference filter comprising:
    an input optical pathway that transmits an input beam;
    an output optical pathway that transmits an output beam;
    an optical path length difference generator having a plurality
        of intermediate pathways that extend in a direction of
        beam propagation, exhibit different effective refractive
        indices, and transmit separate portions of the input beam
        through different optical path lengths;
    a focusing optic that recombines the separate beam portions
        into the output beam having a spectral power distribution
        that is modified with respect to the input beam as a
        result of interference between the separate beam
        portions;
    said optical path length difference generator and said focusing
        optic being aligned with a common reference axis; and
    said intermediate pathways being arranged to provide a
        symmetric distribution of the refractive indices on
        opposite sides of the reference axis.

2. The filter of claim 1 in which said intermediate pathways
are concentric for transmitting radially symmetric portions of the
input beam.

3. The filter of claim 1 in which said intermediate pathways
have equal physical length and are made from a plurality of solid
optical materials having different refractive indices for
transmitting the separate portions of the input beam through
different optical path lengths.

4. The filter of claim 1 in which said intermediate pathways
have equal physical length and are made from combinations of the
same materials in different proportions for exhibiting the different
effective refractive indices.

5. The filter of claim 4 in which the materials within each of
the combinations exist in different physical states.

17

6. The filter of claim 1 in which a reflective surface is formed along said intermediate pathways for reflecting the separate beam portions back through the intermediate pathways, thereby doubling the optical path length differences between the separate
5 beam portions.

7. The filter of claim 1 in which said focusing optic is a reflective surface formed along said intermediate pathways for reflecting the separate beam portions back through the intermediate pathways.

10   8. The filter of claim 7 in which said intermediate pathways converge toward a focal point of said reflective surface.

9. The filter of claim 1 in which said focusing optic and said optical path length difference generator are formed in sections along a length of optical fiber.

15   10. The filter of claim 9 in which said focusing optic is a second of two focusing optics formed in sections along the optical fiber, a first of said focusing optics optically coupling said input pathway to said intermediate pathways, and said second focusing optic optically coupling said intermediate pathways to said output
20 pathway.

11. The filter of claim 10 in which said focusing optics are fiber gradient index lenses.

12. A multi-path interference filter comprising:
an input optical pathway that transmits an input beam;
25   an output optical pathway that transmits an output beam;
an optical path length difference generator having a plurality
        of intermediate pathways that extend in a direction of
        beam propagation;
said intermediate pathways being made from a plurality of
30   solid optical materials having different refractive
        indices for transmitting separate portions of the input
        beam through different optical path lengths; and

18

a focusing optic that recombines the separate beam portions
into the output beam having a spectral power distribution
that is modified with respect to the input beam as a
result of interference between the separate beam
5   portions.

13.   The filter of claim 12 in which said solid optical
materials having different refractive indices extend equal lengths
along said intermediate pathways.

14.   The filter of claim 12 in which said intermediate
10   pathways extend parallel to a reference axis and said solid optical
materials are arranged to provide a symmetric distribution of the
refractive indices on opposite sides of the reference axis.

15.   The filter of claim 12 in which said focusing optic and
said optical path length difference generator are formed in sections
15   along a length of optical fiber.

16.   The filter of claim 15 in which said intermediate
pathways are distinguished by different core materials within the
fiber.

17.   The filter of claim 16 further comprising an external
20   controller that modifies the effective refractive indices of the
intermediate pathways.

18.   A multi-path interference filter comprising:
an input optical pathway that transmits an input beam;
an output optical pathway that transmits an output beam;
25   an optical path length difference generator having a plurality
of equal physical length intermediate pathways that
extend in a direction of beam propagation, exhibit
different effective refractive indices, and transmit
separate portions of the input beam through different
30   optical path lengths;

said equal physical length intermediate pathways being formed by combinations of the same materials in different proportions for exhibiting the different effective refractive indices; and

5   a focusing optic that recombines the separate beam portions into the output beam having a spectral power distribution that is modified with respect to the input beam as a result of interference between the separate beam portions.

10   19.   The filter of claim 18 in which the materials within each of the combinations exist in different physical states.

20.   The filter of claim 19 in which one of the materials is a solid and another of the materials is air.

21.   A multi-path interference filter comprising:

15   an input optical pathway that transmits an input beam;
        an output optical pathway that transmits an output beam;
        an optical path length difference generator having a plurality of equal physical length intermediate pathways that extend in a direction of beam propagation, exhibit

20   different effective refractive indices, and transmit separate portions of the input beam through different optical path lengths;
        a focusing optic that recombines the separate beam portions into the output beam having a spectral power distribution

25   that is modified with respect to the input beam as a result of interference between the separate beam portions; and
        a reflective surface formed along said intermediate pathways for reflecting the separate beam portions back through

30   the intermediate pathways, thereby doubling the optical path length differences between the separate beam portions.

22.   The filter of claim 21 in which said reflective surface has curvature for also functioning as said focusing optic.

20

23. The filter of claim 22 in which said intermediate pathways converge toward a focal point of said reflective surface.

24. A multi-path interference filter for changing a spectral power distribution of a beam of light transmitted between input and
5 output pathways comprising:

an optical path length difference generator optically coupling the input and output pathways and having an array of reflective surfaces that are staggered in a direction of beam propagation between the input and output pathways
10 and are relatively sized to occupy different amounts of transverse area for reflecting correspondingly sized portions of the beam through different physical path lengths between said input and output pathways; and

said reflective surfaces being relatively sized in relation to a
15 transverse energy distribution within the beam to enhance interference between the differently sized portions of the beam.

25. The filter of claim 24 in which said reflective surfaces are oriented to provide a focusing function that couples said optical
20 path length generator to the input and output pathways.

26. The filter of claim 24 in which said reflective surfaces are concentric for transmitting radially symmetric portions of the beam.

27. The filter of claim 24 in which optical path length
25 differences between the differently sized beam portions are further varied by differences between the effective refractive indices of the intermediate pathways.

28. A multi-path interference filter comprising:

input and output optical pathways that transmit a propagating
30 beam of light;

an optical path length difference generator having a stack of planar partially reflective surfaces that are spaced apart in a direction of beam propagation through at least one wavelength of the propagating beam;

21

each of said partially reflective surfaces reflecting a separate portion of the propagating beam through a different physical path length also equal to at least one wavelength in the direction of beam propagation; and

5   a focusing optic that recombines the separate beam portions producing a pattern of interference that modifies a spectral power distribution of the propagating beam.

29.   The filter of claim 28 in which said partially reflective surfaces are formed by partially reflective coatings.

10   30.   The filter of claim 29 in which said partially reflective coatings include distinct areas of reflection and transmission.

31.   The filter of claim 28 in which said partially reflective surfaces are formed by adjacent layers of materials having refractive indices that differ by at least 10 percent.

15   32.   The filter of claim 28 in which a total number of said partially reflective surfaces is no greater than 100.

33.   The filter of claim 32 in which said partially reflective surfaces are spaced apart by at least 10 microns.

34.   The filter of claim 28 in which said focusing optic also
20 functions as a collimator for directing the propagating beam at approximately normal incidence to said plurality of planar partially reflective surfaces of the optical path length difference generator.

35.   The filter of claim 28 in which reflectivities of the partially reflective surfaces differ from one another to further
25 modify the spectral power distribution of the propagating beam.

36.   The filter of claim 28 in which spacings between the partially reflective surfaces differ from one another to further modify the spectral power distribution of the propagating beam.

37.   A multi-path interference filter formed along an optical
30 fiber comprising:

22

a first fiber lens that collimates an input beam having a range
of different wavelengths;

a spacer having a plurality of parallel intermediate pathways
that extend in a direction of beam propagation, exhibit

5   different effective refractive indices, and transmit
separate portions of the collimated beam through
different optical path lengths; and

a second fiber lens that recombines the separate beam portions
into an output beam having a spectral power distribution

10   that is modified with respect to the input beam as a
result of interference between the separate beam
portions,

wherein said spacer is mounted contiguous with said first and
second fiber lenses to form an uninterrupted length of

15   the fiber.

38.   The filter of claim 37 is which both of said first and
second fiber lenses are fiber gradient index lenses.

39.   The filter of claim 37 in which the intermediate pathways
are distinguished by different solid optical materials.

20   40.   The filter of claim 37 in which the different intermediate
pathways are distinguished by combinations of the same materials
in different proportions for exhibiting different effective refractive
indices.

41.   The filter of claim 37 in which said intermediate
25   pathways are relatively sized to occupy different amounts of
transverse area for transmitting correspondingly sized portions of
the input beam.

42.   The filter of claim 41 in which said areas of the
intermediate pathways have annular shapes for transmitting radially
30   symmetric portions of the input beam.

43.   The filter of claim 37 further comprising external
controls for varying the effective refractive indices of the
intermediate pathways.

1/5

FIG.1

FIG.2
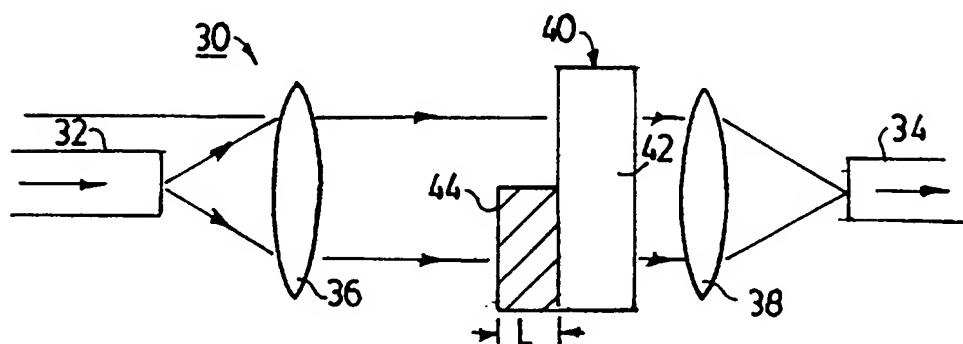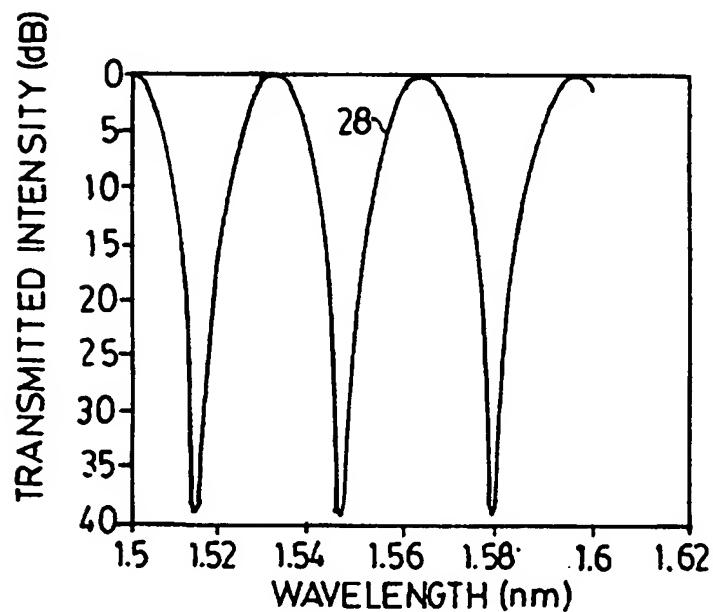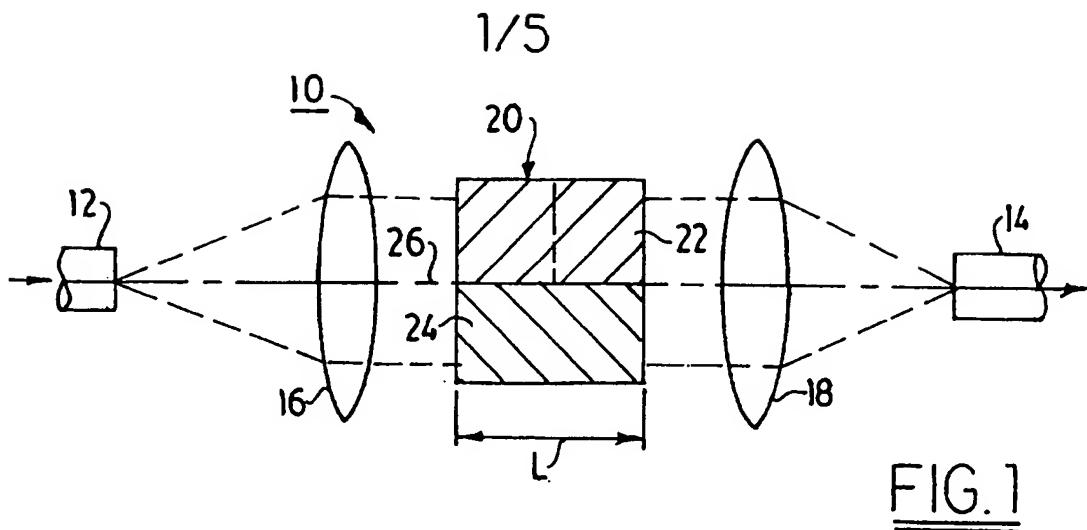
FIG.3
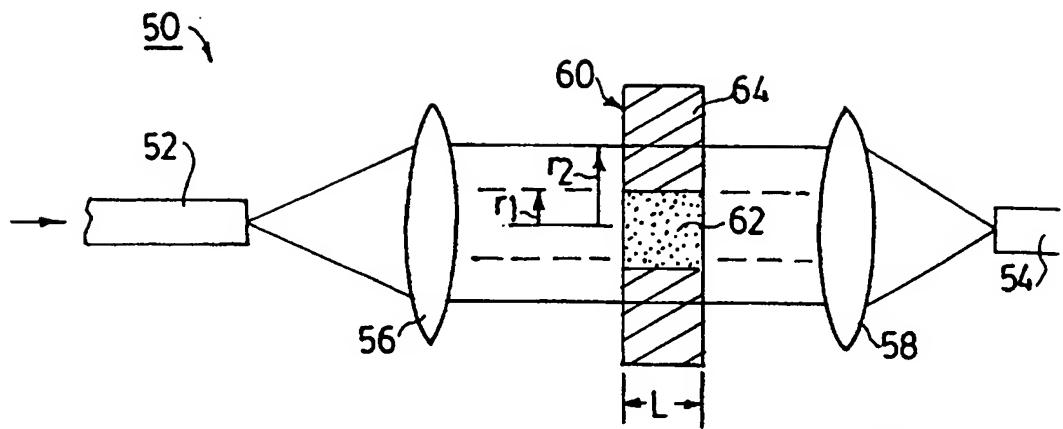
FIG.4
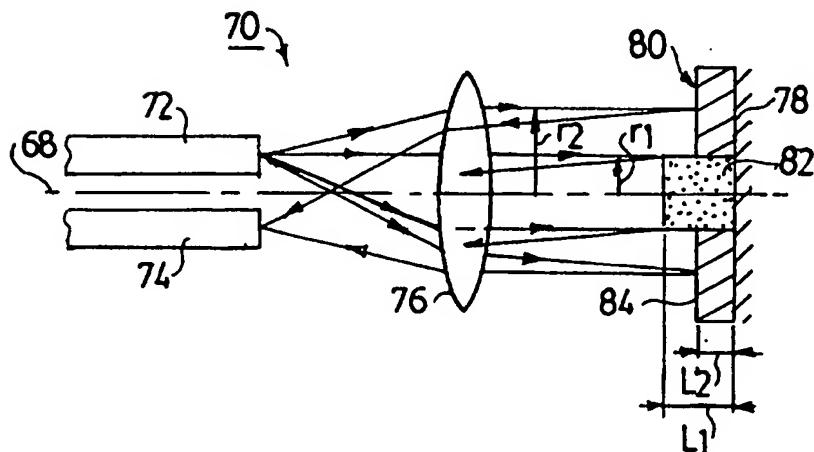
FIG.5
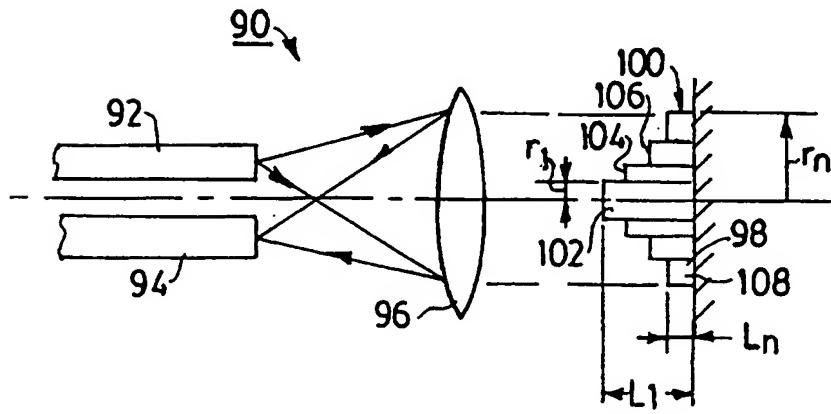
FIG.6
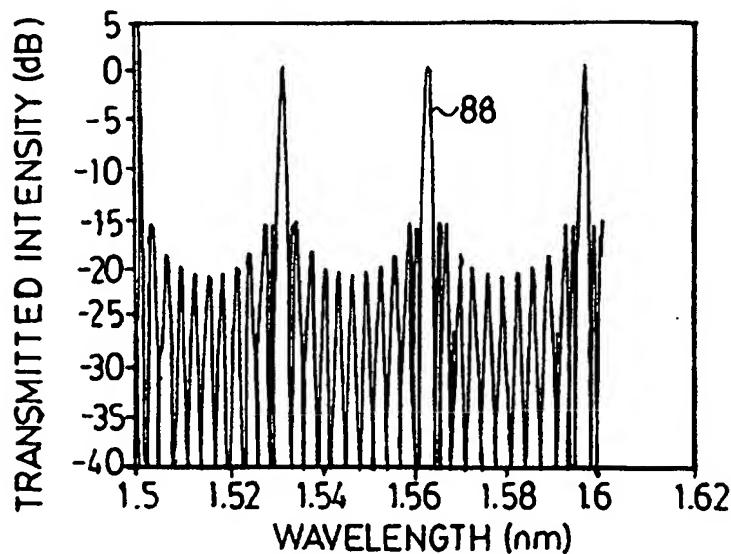
FIG.7
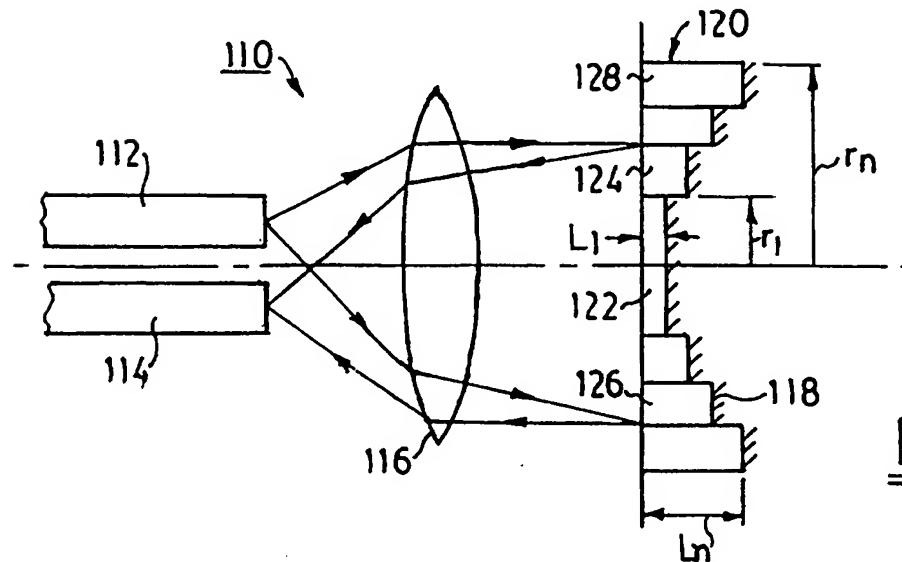
FIG.8
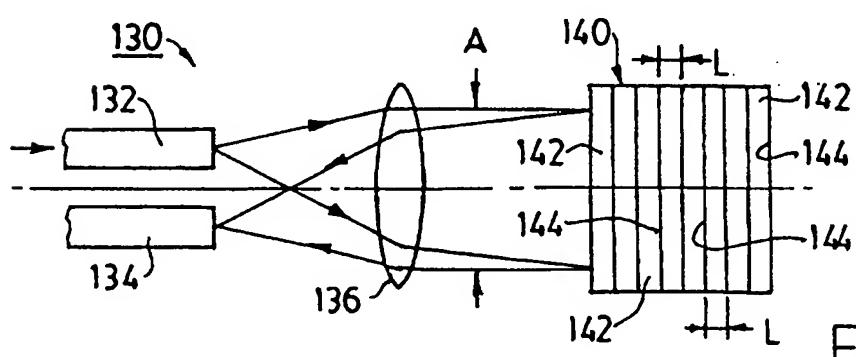
FIG.9
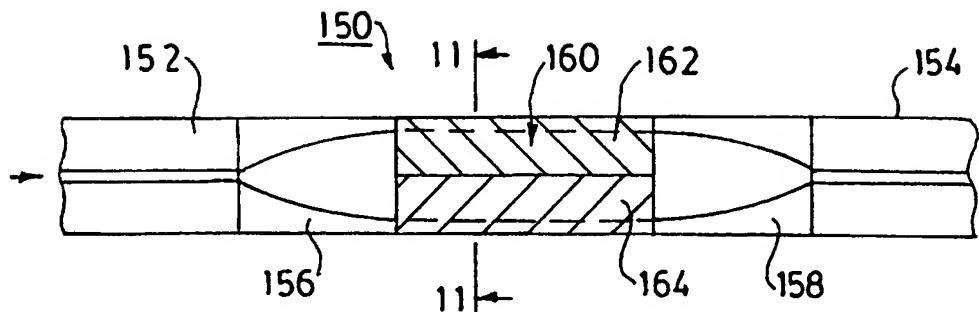
FIG.10

FIG.11

FIG.12

5 / 5

184　　188

186

FIG.13

182

186

FIG.14

LG

190

192

204

200　198

202

196

194

206
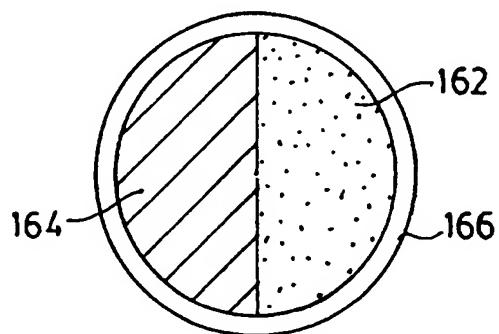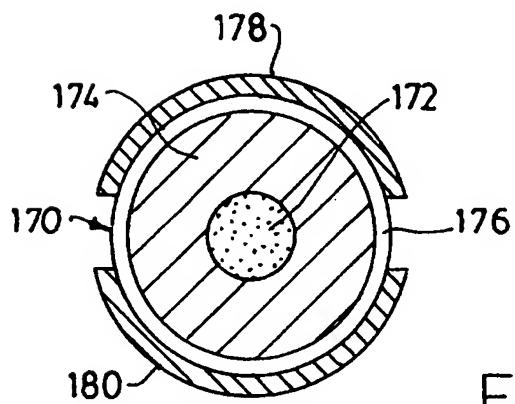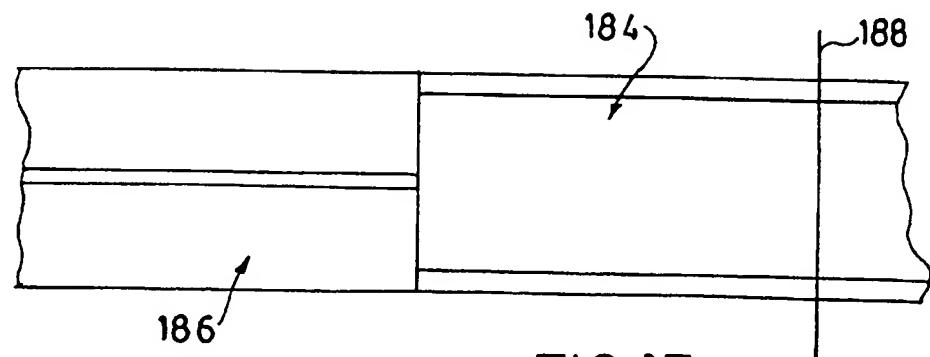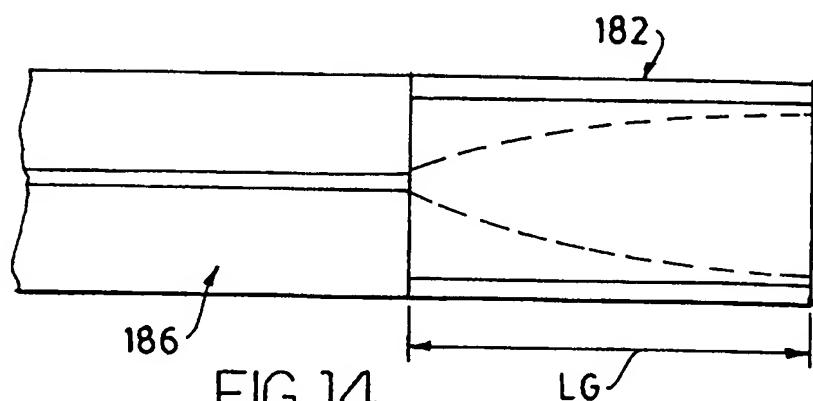
204

FIG.15

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC(6)   :GO2B 5/28, 6/24, 6/293
US CL   :359/577, 584, 589; 385/27, 31
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. :   359/577, 584, 589; 385/27, 31

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

359/578, 579, 580, 581, 586; 385/15, 32, 33, 34, 35, 39, 47

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

APS, search terms: interference, optical path, path difference, focus

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X ---- A	US 3,493,288 A Kaufman et al 03 February 1970 (02/03/70), see entire document.	1,3,4,12,13,15 ,18 ------------------ 2 , 5 - 11,14,16,17, 19-43
X --- A	US 5,459,576 A (Brunfeld et al) 17 October 1995 (10/17/95), see entire document.	1 ---------- 2-43
A	US 4,718,754 A (McIntosh) 12 January 1988 (01/12/88), see entire document.	1-43
A	NETHERCOT, JR., A. H. Light Modulator. IBM tech. dis. bull. December 1963, Vol. 6, No. 7, pages 55 and 56.	1-43

[X] Further documents are listed in the continuation of Box C.   [ ] See patent family annex.

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance		
"E"	earlier document published on or after the international filing date	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed	"&"	document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
01 APRIL 1997	1 4 MAY 1997

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	JON W. HENRY
Facsimile No. (703) 305-3230	Telephone No. (703) 305-6106
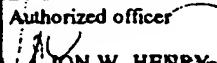
Form PCT/ISA/210 (second sheet)(July 1992)*

INTERNATIONAL SEARCH REPORT

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5,140,464 A (KYOGOKU ET AL) 18 August 1992 (08/18/92), see entire document.	1-43
A	DE 2136266 (SCHOLLMEIER ET AL) 01 February 1973 (02/01/73), see entire document.	1-43